

Puffing up early-type galaxies by baryonic mass loss: numerical experiments

Cinthia Ragone-Figueroa¹*, Gian Luigi Granato²†

¹ *Instituto de Astronomía Teórica y Experimental, IATE, CONICET-Observatorio Astronómico, Universidad Nacional de Córdoba, Laprida 854, X5000BGR, Córdoba, Argentina*

² *Istituto Nazionale di Astrofisica INAF, Osservatorio Astronomico di Trieste, Via Tiepolo 11, I-34131 Trieste, Italy*

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ABSTRACT

Observations performed in the last few years indicate that most massive early-type galaxies (ETGs) observed at redshift $z \gtrsim 1$ exhibit sizes smaller by a factor of a few than local ETGs of analogous stellar mass. We present numerical simulations of the effect of baryonic mass loss on the structure of a spheroidal stellar system, embedded in a dark matter halo. This process, invoked as a possible explanation of the observed size increase of ETGs since $z \sim 2$, could be caused either by QSO/starburst driven galactic winds, promptly ejecting from Early Type Galaxies (ETGs) the residual gas and halting star formation (galactic winds), or by stellar mass returned to the ISM in the final stages of stellar evolution. Indeed, we find that a conceivable loss of $\sim 50\%$ of the baryonic mass can produce a significant size increase. However, the puffing up due to galactic winds occurs when the stellar populations are much younger than the estimated ages $\gtrsim 0.5$ Gyr of compact high- z ETGs. Therefore, while it may have had a role in deciding the final structure of ETGs, it cannot explain the evolution observed so far of their size-mass relation; its signature should be searched for in much younger systems. Conversely, the mass loss due to stellar evolution could cause a relatively modest expansion of passively evolving stellar systems later on, contributing to, without dominating, the observed evolution of their mass-size relationship.

Key words: galaxies: formation - galaxies: evolution - galaxies: elliptical - quasars: general - method: numerical

1 INTRODUCTION

During the last years it has been established that most massive early-type galaxies (ETGs) observed at redshift $z \gtrsim 1$ exhibit sizes smaller by a factor of a few than local ETGs of analogous stellar mass (e.g. Daddi et al. 2004; Trujillo et al. 2006, 2007, 2011; Longhetti et al. 2007; Toft et al. 2007; Zirm et al. 2007; van der Wel et al. 2008; van Dokkum et al. 2008; Cimatti et al. 2008; Buitrago et al. 2008; Damjanov et al. 2009; Ryan et al. 2010).

The possibility that the size evolution is, at least in part, apparent and due to some subtle systematic effect has not been completely ruled out. Discussed caveats include a centrally concentrated source (such as an AGN or central starburst), age gradients, un-detected low surface bright-

ness external regions at high z , or a top-heavy IMF affecting mass estimates (see Daddi et al. 2005; Van Dokkum et al. 2008; La Barbera et al. 2009; Mancini et al. 2010; Hopkins et al. 2009, 2010). Moreover, very recent observational results claim some co-existence of compact and normal size ETGs, both at high (Mancini et al. 2010; Onodera et al. 2010; Saracco et al. 2010) and low redshift (Valentinuzzi et al. 2010).

However, nowadays most authors agree that the observational results are dominated by a real size evolution. The proposed interpretations are related either to the effects of mergers or to the loss of a substantial fraction of mass from the galaxy.

Khochfar & Silk (2006) presented a semi-analytic model where the size evolution is substantial only for galaxies more massive than $10^{11} M_{\odot}$, and results from massive galaxies at high redshifts forming in gas-rich dissipative mergers, whilst galaxies of the same mass at low redshifts form from gas-

* Email: cin@mail.oac.uncor.edu

† Email: granato@oats.inaf.it

poor mergers. However, current observations indicate sizeable evolution also in much smaller systems (e.g. Ryan et al 2010). Similar ideas have been explored by Hopkins et al. (2009), in a more phenomenological model incorporating results of a large suite of numerical simulations of mergers.

Actually, the size increasing effects of *major* (wherein the two merging galaxies have comparable masses) *dry* (i.e. without a significant collisional gas component) mergers has been often discussed. By converse, in *wet* mergers, the presence of a dissipative gas component limits the gain in size. However, even the former process faces a few problems. The most basic is that it would move galaxies too slowly toward the local size-mass relationship (Cimatti et al 2008; Bezançon et al. 2009; Damjanov et al. 2009; Saracco et al 2009). This is because, according to simple virial theorem argument, confirmed by a number of numerical simulations, in major dry mergers the size increases almost linearly with the mass, and possibly somewhat less (e.g. Ciotti & van Albada 2001; Nipoti et al. 2003; Boylan-Kolchin et al. 2006; Naab et al. 2009). This dependence is too close to the observed local mass-size relationship $r \propto M^{0.56}$ (Shen et al. 2003) to explain the evolution in a reasonable number of merging events.

The most promising *merging* mechanism to explain the size increase seems to be a series of late minor dry merging events. These would add stars in the outer parts of passive high- z galaxies, in such a way to produce a size increase that can scale as steep as M^2 (e.g. Naab et al. 2009; Oser et al. 2010). Actually, Hopkins et al. (2010), considering the various proposed channels for observed size evolution, concluded that minor dry mergers are the best candidate to dominate, though other channels should have a non negligible role.

In this paper, we will test the possible contribution of the *puffing-up* process. This envisages that the expansion in size is driven by the expulsion of a substantial fraction of the gas out of the galaxy either by AGN and/or supernova driven galactic winds (Fan et al. 2008, 2010), or by the expulsion of gas associated to stellar evolution (Damjanov et al. 2009). In the former case the expulsion timescale would be short, likely not much longer than the dynamical timescale, at least when driven by the AGN, whilst in the latter an important mass loss could last even $\sim 0.5 - 1$ Gyr, depending on the IMF and on stellar evolution details.

While the works by Fan et al. (2008, 2010) used as a reference the specific semi-analytic model by Granato et al. (2004) for the co-evolution of ETGs and SMBH (henceforth G04), this kind of puffing-up due to baryonic mass loss from the galaxy has a broader applicability. Indeed, virtually all modern models of galaxy formation give a prominent role to AGN and/or SNe driven galactic wind, ejecting from the galactic region a substantial fraction of gas (for a recent review, see Benson 2010). Thus, it is very likely that this puffing up played a role in deciding the final sizes of ETGs, at some point over their history. However, it is still an open question whether this role has been major, and, in particular, whether it can explain the available observations. The aim of the present work is to provide a step to clarify it.

The idea that a puffing-up mechanism should at some point have had occurred rests on many hints, nowadays coming from a complex interplay between observations and theory, suggesting that ETGs are the result of an intense phase of high- z star formation activity, possibly traced by the sub-

mm selected galaxy population. It is unlikely that these extreme "starburst", induced by fast collapse and/or by rapid merging of gas rich systems, have been suddenly terminated by simple gas consumption. It is instead usually envisaged that some strong feedback was capable to eject from the galaxy, on a relatively short timescale, a substantial fraction of its baryonic mass, in the form of gas not yet converted into stars (a process usually referred to as "galactic wind or superwind"; see e.g. Benson et al. 2003; Pipino, Silk & Matteucci 2009; for observational indications of these high- z galactic outflows see Lípari et al. 2009 and Prochaska & Hennawi 2009, and references therein). In the past years it has been pointed out that the most likely candidate to power such a process, at least in massive systems, is QSO activity (e.g. Silk & Rees 1998; Fabian 1999; Granato et al. 2001, 2004; Benson et al 2003; Cattaneo et al. 2006; Monaco et al. 2007; Sijacki et al. 2007; Somerville et al. 2008; Johansson et al. 2009; Ciotti, Ostriker & Proga 2009).

Additionally, after the termination of this huge star-forming phase, it is likely that the galaxy lost another significant fraction of its baryonic mass, due to stellar evolution (supernova explosions and stellar winds).

Independently of the still uncertain details of the formation mechanism of ETGs, or more generally of the spheroidal component of galaxies, it seems timely to investigate with aimed numerical simulations the effects of the expulsion of a significant fraction of baryonic mass from a spheroidal system embedded in a dark matter (DM) halo.

The plan of the paper is the following. In Section 2 we recall previous results on a problem sharing similarities with that considered here: the dynamical evolution of young star clusters after dispersion of the parent gas cloud. These results inspired the proposal that the size evolution of ETGs could be due to the puffing up mechanism, and were adopted as a rough approximation for quantitative considerations. Section 3 we describe the simulation technique and the initial conditions, the results are presented in Section 4, and discussed, in the context of observed size evolution of ETGs, in the final Section 5. We use the concordance cosmology (Komatsu et al. 2009), i.e., a flat universe with matter density parameter $\Omega_M = 0.3$ and Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE STAR CLUSTER APPROXIMATION

A process somewhat similar to the puffing up of ETGs by mass loss has been addressed several times, both analytically and numerically, in the context of the dynamical evolution of star clusters. Again, the mass loss is due to (i) the indirect and combined effects of stellar winds and supernova explosions, soon driving out the significant fraction of gas not used in star formation, or (ii) directly to stellar evolution. As for star clusters, the latter contribution includes the gas ejected from the stars by winds and explosions, but also the compact remnants that may get at birth a kick velocity sufficient to be ejected from the system. The most obvious differences, with respect to the puffing-up of ETGs, are the absence of an embedding dark matter halo and, to a lesser extent, the importance of two-body collisions.

Biermann & Shapiro (1979) and Hills (1980), under simplifying assumptions to allow an analytical treatment, found

that the size evolution depends on the ejection timescale. If this is short compared to the dynamical time (hereafter *fast ejection*), conservation of specific kinetic energy yields for the expansion factor

$$\frac{R_f}{R_i} = \frac{\epsilon}{2\epsilon - 1} \quad (1)$$

in terms of the ratio between the final and initial mass $\epsilon \equiv M_f/M_i$; note that for $\epsilon \leq 0.5$ the system becomes unbound and dissociates. On the other hand, if the ejection timescales is much longer than the dynamical one, conservation of adiabatic invariants yields the size evolution

$$\frac{R_f}{R_i} = \frac{1}{\epsilon} ; \quad (2)$$

Thus, fast expulsion is more effective in increasing the size, while, if the expulsion is slow enough (adiabatic), the system remains bound independently of ϵ .

These relationships have been checked and substantially confirmed by several numerical simulations of star clusters dynamics, starting from the pioneeristic work by Tutukov (1978). However, due to a few effects not accounted for in analytical works, a portion of the system remains bound even if ϵ is somewhat smaller than 0.5 and the mass loss is fast (see Baumgardt & Kroupa 2007 and references therein). Numerical experiments show also that, after fast mass loss ends, the system rapidly reaches a maximum transient expansion within 10 – 15 dynamical times, while a new equilibrium is attained over 30 – 40 dynamical times (e.g. Geyer & Burkert, 2001; Goodwin & Bastian, 2006; Baumgardt & Kroupa, 2007).

Fan et al. (2008, 2010) tentatively tested against available data a QSO driven puffing up scenario for ETGs, resting on the G04 model of joint evolution of SMBH and spheroids, and adopting the above relationships coming from star cluster dynamics. Their findings are to some extent encouraging, but, as remarked by Mancini et al. (2010), a closer analysis reveals that the expansion time-scale seems far too short to explain the relatively old ($\gtrsim 1$ Gyr) stellar ages claimed for high-z compact galaxies. A similar, albeit less dramatic, problem has been pointed out by Damjanov et al. (2009) when trying to explain the observed size evolution by means of mass loss due to stellar evolution. In this case the timescale of mass loss are dictated by stellar evolution, and the expected expansion is adiabatic.

However, assuming the above recipes for ETGs is only a zeroth order approximation, since in ETGs the DM halo is expected to affect the efficiency and timescale of the size evolution, and to prevent galaxy disruption even when a major fraction of baryonic mass is lost. In the following, our purpose is to investigate these effects via simple but aimed numerical simulations.

3 NUMERICAL METHOD AND SETUP

The purpose of the simulations is to investigate the evolution of collision-less particles (stars and DM) under a change of gravitational potential due to a loss of baryonic mass of the system. The escaping mass can be either the gas which has not been converted into stars during the star forming phase of the spheroid, or the mass lost from stars in form of stellar winds and SNe explosions. In any case, we assume as

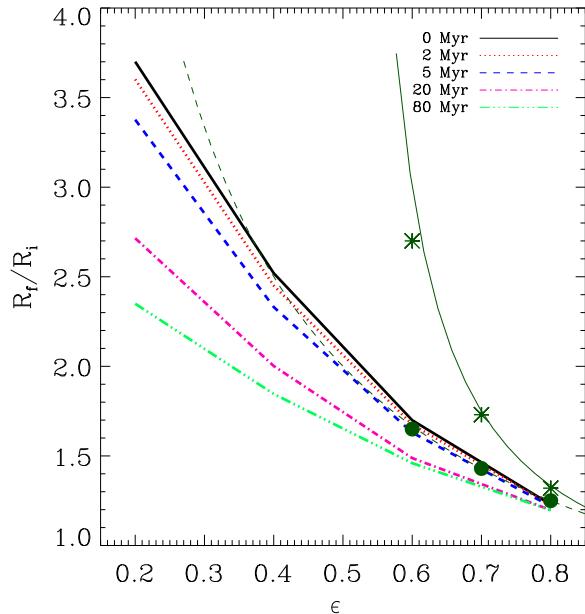


Figure 1. Half mass radius increase R_f/R_i due to baryonic mass loss as a function of the parameter $\epsilon \equiv M_{B,fin}/M_{B,ini}$, for different ejection times Δt (thick lines are with DM included). The thin lines illustrate the size increase according to the analytic approximation, meant for a system not embedded in a DM halo, of Eq. (1) (solid, fast ejection) and (2) (dashed slow ejection). The points show examples of runs without DM halo included (asterisks for fast ejection $\Delta t = 0$ and circles for slow ejection $\Delta t = 80$ Myr)

given, and due to “external” causes (such as SNe and AGN feedbacks, or stellar evolution), the temporal dependence of this mass loss (Eq. 12), which we put by hand, and we simulate the ensuing evolution of collision-less mass distributions. Therefore we don’t have to treat the gas dynamics. This is the same approach followed in most simulations of puffing-up of star clusters (e.g. Boily & Kroupa, 2003; Goodwin & Bastian, 2006; Baumgardt & Kroupa, 2007).

We used the N -body code *GADGET-2* (Springel et al. 2005) to perform simulations with 10^6 and 5×10^6 particles. None of the presented results show any noticeable difference in the two cases, which assures us that the mass resolution is sufficient for the purposes of the present study. Half of the particles are used to sample the baryonic and dark matter components respectively.

The density distribution of DM particles is assumed to follow the standard NFW (Navarro, Frenk & White 1997) shape

$$\rho_{\text{DM}}(r) = \frac{M_{\text{vir,DM}}}{4\pi R_{\text{vir}}^3} \frac{c^2 g(c)}{\hat{r}(1+c\hat{r})^2} , \quad (3)$$

where $M_{\text{vir,DM}}$ is the halo virial mass in DM (the DM mass inside R_{vir}), $\hat{r} = r/R_{\text{vir}}$, c is the concentration parameter and $g(c) \equiv [\log(1+c) - c/(1+c)]^{-1}$.

The virial radius, R_{vir} , is by definition the radius within which the mean density is $\Delta_{\text{vir}}(z)$ (a quantity classically coming from the spherical top-hat collapse model) times the mean matter density of the universe $\rho_u(z)$:

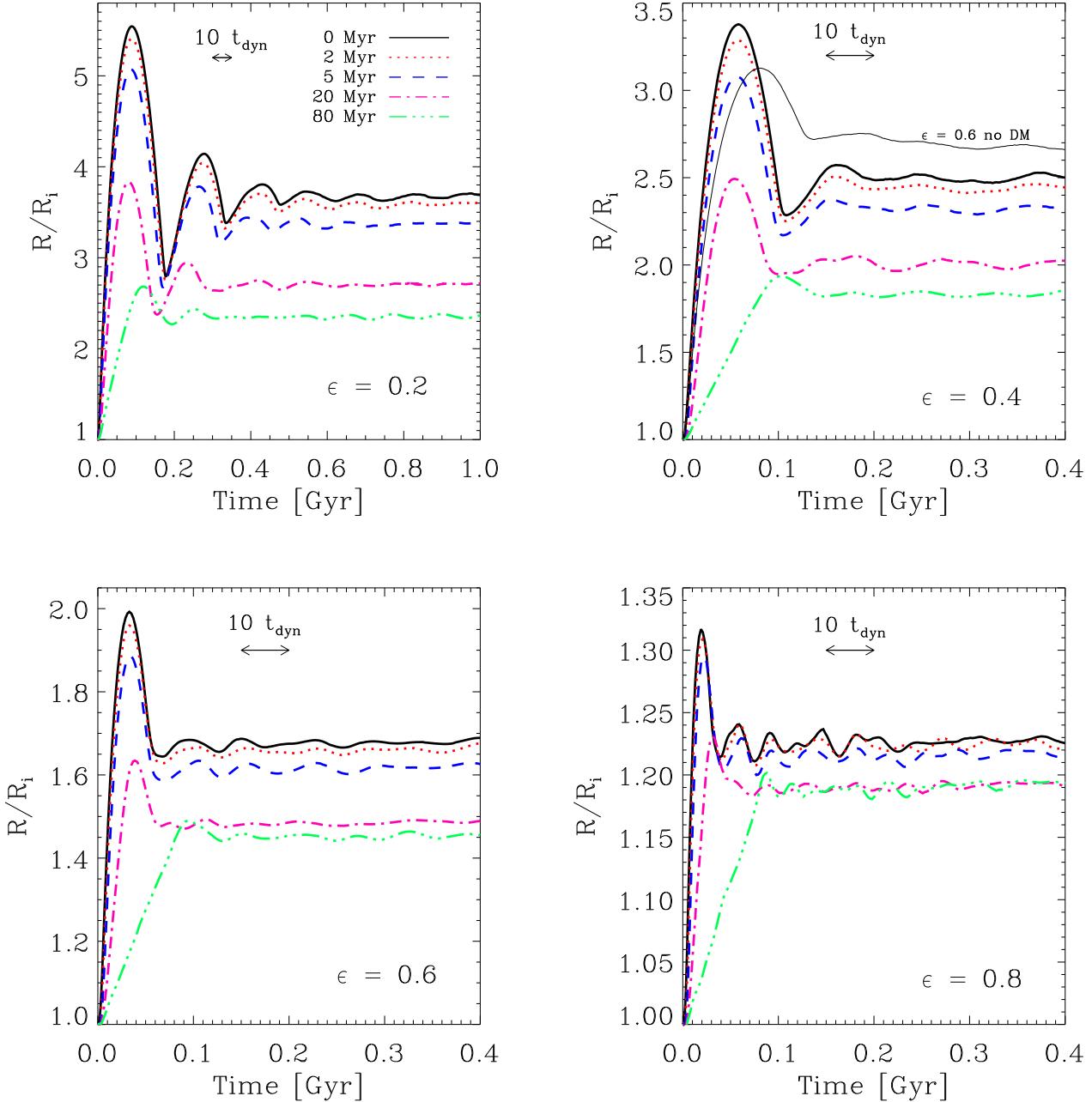


Figure 2. Ratio R/R_i of the current to the initial half-mass radius as a function of time, for different values of the diet parameter ϵ and of the ejection times Δt , as indicated in the panels. The thin solid line in the top right panel shows the evolution of a model not including the DM halo, for $\epsilon = 0.6$. Note that the latter is shown in the panel corresponding to $\epsilon = 0.4$ (for the cases including DM) since the vertical scale is more adequate. The double arrows show the duration of a $10 t_{\text{dyn}}$ time interval. For the adopted initial conditions, $t_{\text{dyn}} \simeq 5$ Myr. See text for explanations.

$$R_{\text{vir}} = \left[\frac{3}{4\pi} \frac{M_{\text{vir}}}{\Delta_{\text{vir}}(z) \rho_u(z)} \right]^{1/3}, \quad (4)$$

The overdensity $\Delta_{\text{vir}}(z)$, for a flat cosmology, can be approximated by

$$\Delta_{\text{vir}}(z) \simeq \frac{(18\pi^2 + 82x - 39x^2)}{\Omega(z)}, \quad (5)$$

where $x = \Omega(z) - 1$ and $\Omega(z)$ is the ratio of the mean matter density to the critical density at redshift z (Bryan & Norman 1998).

The corresponding mass distribution is written

$$M_{\text{DM}}(< r) = M_{\text{vir,DM}} g(c) \left[\log(1 + c \hat{r}) - \frac{c \hat{r}}{(1 + c \hat{r})} \right]. \quad (6)$$

To cope with the divergence of the NFW mass distribution,

we introduce an exponential cut at $3R_{\text{vir}}$, which very safely contains the region where the baryonic component is important. We performed also a few test runs with the cut at $2R_{\text{vir}}$, verifying that none of the discussed quantities is affected by this choice.

For the baryonic particles (stars and gas), we assume that they follow an Hernquist (1990) profile, which provides a reasonable description of stellar density in local spheroids:

$$\rho_B(r) = \frac{M_B}{2\pi} \frac{a}{r(r+a)^3} ; \quad (7)$$

The corresponding mass distribution is

$$M_B(< r) = M_B \left(\frac{r}{r+a} \right)^2 ; \quad (8)$$

so that the half-mass radius is related to the scale radius a by $R_{1/2} = (1 + \sqrt{2})a$ and, assuming a mass to light ratio independent of r , the effective radius is $R_e \simeq 1.81a$.

In the following, unless otherwise specified, by *dynamical time* t_{dyn} we mean the initial (i.e. before any mass loss and expansion) dynamical time, computed at $R_{1/2}$.

$$t_{\text{dyn}} = \left[\frac{R_{1/2}^3}{2G(M_B/2 + M_{\text{DM}}(< R_{1/2}))} \right]^{1/2} \quad (9)$$

For our standard initial conditions (see below) the contribution of DM to the mass inside $R_{1/2}$ amounts to $\simeq 20\%$. Thus t_{dyn} can be estimated (within 10%) neglecting it:

$$t_{\text{dyn}} \simeq 2.3 \left(\frac{R_e}{1 \text{kpc}} \right)^{1.5} \left(\frac{M_B}{10^{11} M_{\odot}} \right)^{-0.5} \text{Myr} \quad (10)$$

Given the density runs, we obtain the 1D velocity dispersion by integrating the Jeans equation under the assumption of isotropic conditions:

$$\sigma_X^2(r) = -\frac{1}{\rho_X(r)} \int_r^\infty dr' \frac{G M_{\text{TOT}}(< r')}{r'^2} \rho_X(r') , \quad (11)$$

where X stands for B or DM, and $M_{\text{TOT}}(< r) = M_{\text{DM}}(< r) + M_B(< r)$. By evolving the particle system for several dynamical times, we get confident that it is actually in (quasi-)static statistical equilibrium.

Starting from this initial setup, we introduce a mass loss, intended to emulate the various possible effects described above, by removing exponentially over an ejection time Δt a fraction $1 - \epsilon$ of the baryonic mass :

$$M_B(t) = M_{B(t=0)} \exp \left(\frac{\ln \epsilon}{\Delta t} t \right) , \quad (12)$$

For instance, this simple functional form provides an acceptable description of the gas removal due to QSO feedback in the G04 semi-analytic model, with an ejection timescale of the order of 20-30 Myr for a wide range of the model parameters.

The mass loss is practically attained by decreasing correspondingly in time the mass of the baryonic particles sampling the density field. After the end of the mass loss period, we let the system to evolve till it reaches, if any, a new equilibrium configuration.

The reference value for the initial (i.e. before any mass loss) ratio of virial mass (total mass within the virial radius) to baryonic mass is $M_{\text{vir}}/M_{B(t=0)} = 25$. In a recent analysis consistent with previous works, Monster et al. 2010 find

that this ratio should be, in the local universe, about 50 for DM haloes of $\sim 5 \times 10^{12} M_{\odot}$. However, to get a significant puffing-up, the system should lose something of the order of 50% of its baryonic mass. Thus, we set as initial condition a ratio twice smaller than that.

We set $M_{\text{vir}} = 10^{13} M_{\odot}$ in all simulations. Nevertheless, our results apply to different values of M_{vir} , provided that the ratios of scale radii and masses in the two components (DM and baryons) are not changed, and that the time is measured in units of dynamical time $t_{\text{dyn}} \propto \rho^{-1/2}$.

We adopt a concentration parameter $c = 4$, a typical value at galactic halo formation (see Zhao et al. 2003; Klypin, Trujillo-Gomez, & Primack 2010), and $R_{\text{vir}} \simeq 170$ kpc, which is the value given by Eq. 4 and Eq. 5, for a $M_{\text{vir}} = 10^{13} M_{\odot}$ halo virialized at $z = 3$.

We set $a = 1.5$ kpc ($R_e \simeq 2.7$ kpc). This seems a value adequate to study the evolution of the system in the plane effective radius R_e vs. stellar mass M_* . Indeed, assuming that about half of the initial baryonic mass is in form of stars, the system would lie initially a factor $\simeq 2.5$ below the local mass-size relationship for ETGs. The initial (i.e. before mass loss and expansion, Eq. 9) dynamical time is $t_{\text{dyn}} \approx 5$ Myr. Note that a smaller initial size would shorten the dynamical time, exacerbating the problems pointed out in Section 5.

In summary, the parameters affecting the results of our simulations are the ratio of mass between the total and baryonic components $M_{\text{vir}}/M_{B(t=0)}$; the corresponding ratio of scale-lengths R_{vir}/a ; the fraction of baryonic mass lost $(1 - \epsilon)$, and the time Δt over which the loss occurs. We performed simulations covering broad ranges of the latter two quantities, while in most runs we kept the former two at the fiducial values discussed above. We checked however that none of our qualitative conclusion is affected by factor ~ 2 variations of them, and likely even by larger ones (see discussion at the end of Section 4).

4 RESULTS

As a preliminary sanity check, we ran simulations without DM with ejection times $\Delta t = 0$ Myr and 80 Myr, i.e., much shorter or much longer than t_{dyn} , respectively. The ratio of the final to the initial half-mass size R_f/R_i generally agrees well with the expectations given by Eq. (1) and (2) (see Fig. 1). However, when the mass loss is fast and approaches 50%, the analytical formula Eq. (1) increasingly over-predicts the numerical result, underlying the well known fact that the divergence does not occur at $\epsilon = 0.5$ in numerical simulations. This is in keeping with previous findings (e.g. Geyer & Burkert 2001).

We now turn to cases with DM included. Fig. 1 illustrates the size expansion as a function of the fraction of remaining baryonic mass $\epsilon = 0.2, 0.4, 0.6$, and 0.8 , for different ejection times $\Delta t = 0, 2, 5, 20$, and 80 Myr. The expansion increases with decreasing ϵ and Δt , but it is milder with respect to the corresponding purely baryonic case. In particular, the system is no longer disrupted even when the ejection is impulsive ($\Delta t = 0$) and ϵ is as low as $= 0.2$; this is expected since DM constitutes the dominant source of gravitational potential at large radii. We have verified, with a few sample runs, that the case with $\Delta t = 80$ Myr is represen-

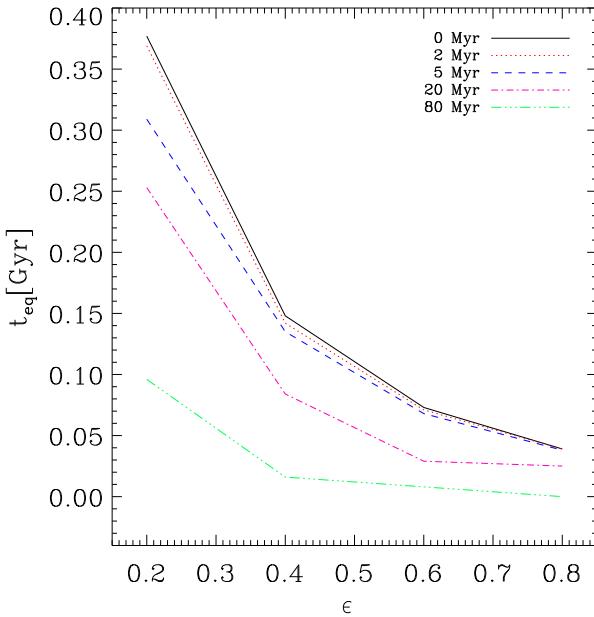


Figure 3. The time needed, after the end of mass loss, to recover an equilibrium configuration as a function of the parameter $\epsilon \equiv M_{B,fin}/M_{B,ini}$, for different ejection times Δt . This time is defined by the epoch after which the size never changes more than 10% with respect to the final value.

tative of the "slow expulsion" regime $\Delta t \gg t_{dyn}$. In other words, the expansion factor do not decrease any more for larger values of Δt . Note also that, as already mentioned, $\Delta t = 20$ is likely the case that best approximates, among those shown, the QSO driven gas expulsion predicted by the G04 model (see Fig. 7), and considered by Fan et al. (2008; 2010). The corresponding expansion is significantly smaller than that achieved for instantaneous ejection.

Fig. 2 shows in detail the time evolution of the system size during and after the ejection. For sake of comparison we include also a case without DM. For $\Delta t \gg t_{dyn}$, the size increases mostly during the mass loss, and stabilizes soon after Δt , so that the system is actually in quasi-equilibrium during the ejection process; contrariwise, for impulsive ejection with $\Delta t \ll t_{dyn}$ the initial equilibrium is totally broken, and the system expands significantly more. The size undergoes damped oscillations before stabilizing, more important for smaller ϵ or Δt . Fig. 3 shows the time needed, after the end of mass loss, to recover a substantially stable configuration. This turns out to be shorter than the corresponding time without the DM component, as expected on an intuitive basis, due to the stabilizing effect of the latter (for instance, compare the thin solid curve in the top-right panel of Fig. 2, with the thick solid curve in the bottom-left panel).

Fig. 4 shows the evolution of the average stellar velocity dispersion. During the size expansion the system cools down and the stellar random motions slow, reducing the average dispersion. The net effect is found to be much evident for strong ejection (small ϵ) but almost independent of the ejection time Δt .

In Fig 5 we illustrate the effects of baryon expulsion on the density profiles of both components. For $\epsilon \geq 0.6$ and

fast expulsion, the baryonic component, after a violently disturbed phase, eventually recovers a density distribution reasonably well described by the Hernquist formula, albeit with a larger scalelength (for instance $a = 2.34$ with reduced $\chi^2 = 2.6$ for $\epsilon = 0.6$, shown in the figure). By converse, at lower ϵ , the Hernquist fit becomes increasingly unacceptable for the final equilibrium profile (e.g. $a = 5$ and reduced $\chi^2 = 41$ for $\epsilon = 0.2$). This is not surprising, since the final bound state is increasingly dictated by the presence of the embedding DM halo. Actually for $\epsilon \lesssim 0.5$ the system would dissolve if not for the halo. In any case slower expulsion with same ϵ yields lower deviations from the Hernquist functional form. In particular, for $\epsilon \geq 0.6$ and $\Delta t = 80$ Myr the Hernquist formula provides a good description of the density distribution even during the mass loss-expansion phase.

For DM, on large scales the profile is unaffected, while in the inner region the baryon expansion drags an expansion of the DM particles. As a result, the DM profile in the galactic region is always flattened to some level with respect to the original NFW shape.

Fig 6 shows the sensitivity of our results to the parameters of the initial baryonic configuration. As expected, the effects are in the sense that, whenever the DM contributes more (less) to the mass inside the region occupied by the baryonic system, the latter expands less (more). This may occur by increasing (decreasing) the ratios $M_{vir}/M_{B(t=0)}$ or a/R_{vir} . Note the trade-off between variations in initial size and its amplification due to mass loss. As a result, the final size is relatively insensitive to the initial one, particularly for fast expulsion. For instance, when the impulsive mass loss is 60% ($\epsilon = 0.4$), a factor 4 change of the adopted initial R_e , yields only a factor ~ 1.5 change in the final R_e (blue points and arrows in Fig 6). This could have a role in explaining the relatively low scatter of the observed local mass-size relationship. Also, an increase (decrease) of $M_{B(t=0)}$, keeping fixed all other parameters, and in particular M_{vir} , yields a larger (smaller) expansion. This tends to keep the expansion close to that required to maintain the final state of the system in the region of local mass-size relation (red points and arrows in Fig 6).

5 DISCUSSION AND CONCLUSIONS

An inspection to the previous figures, in particular to Fig. 2 (and to a lesser extent Fig. 3), reveals the main problem to explain the *observed* size evolution of ETGs with the puffing-up scenario. On one hand, our simulations confirm that, even in presence of a DM component, a factor ~ 2 increase in size can be expected in any galaxy formation model in which the spheroid loses $\sim 50\%$ of its baryonic mass, in particular when this happens on a timescale of the order of the dynamical timescale. Moreover, the expansion is larger for systems initially more compacts, resulting in an interesting self regulation of the final size (Fig. 6). However, if this mass is constituted by the star forming gas, in scenarios in which a galactic wind suddenly sterilizes the galaxy (such as in the G04 model considered by Fan et al. 2008, 2010), the puffing-up occurs far too close to the last episode of star formation. Indeed, the galaxy is predicted to be smaller than the final size only for a very short time after expulsion, less

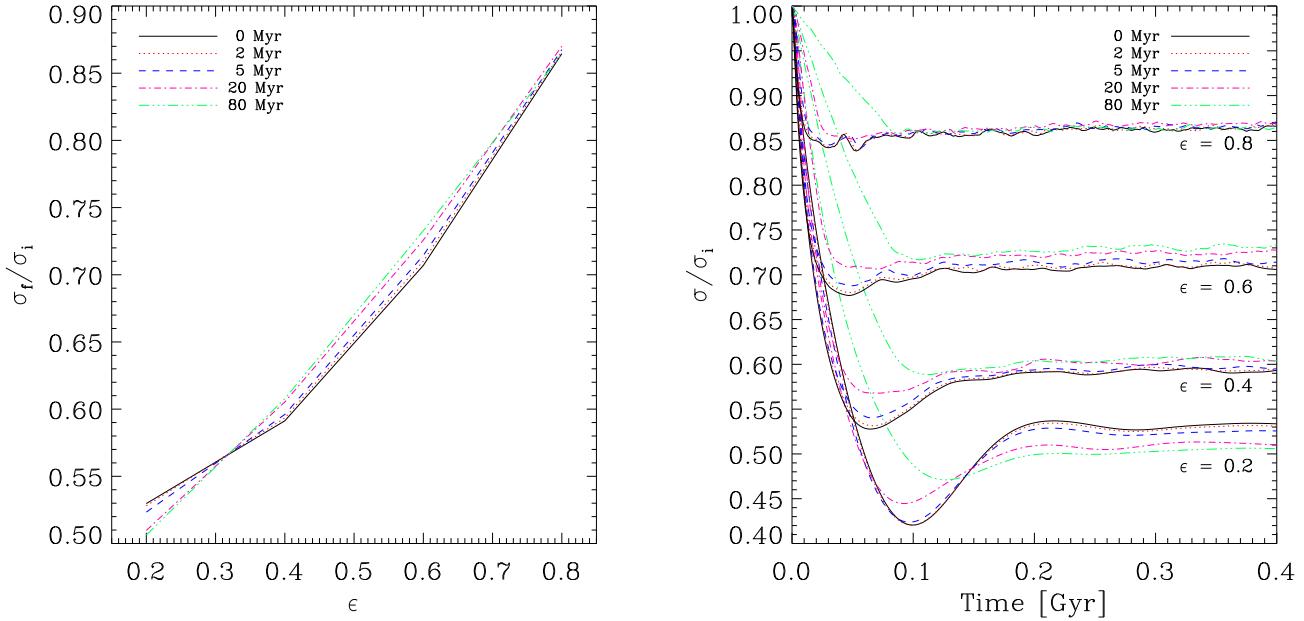


Figure 4. Left panel: Ratio σ_f/σ_i of the final to initial mean 3D stellar velocity dispersion as a function of ϵ , for different ejection times Δt . Right panel: same as a function of time, for different values of the diet parameter ϵ (as labeled) and of the ejection times Δt .

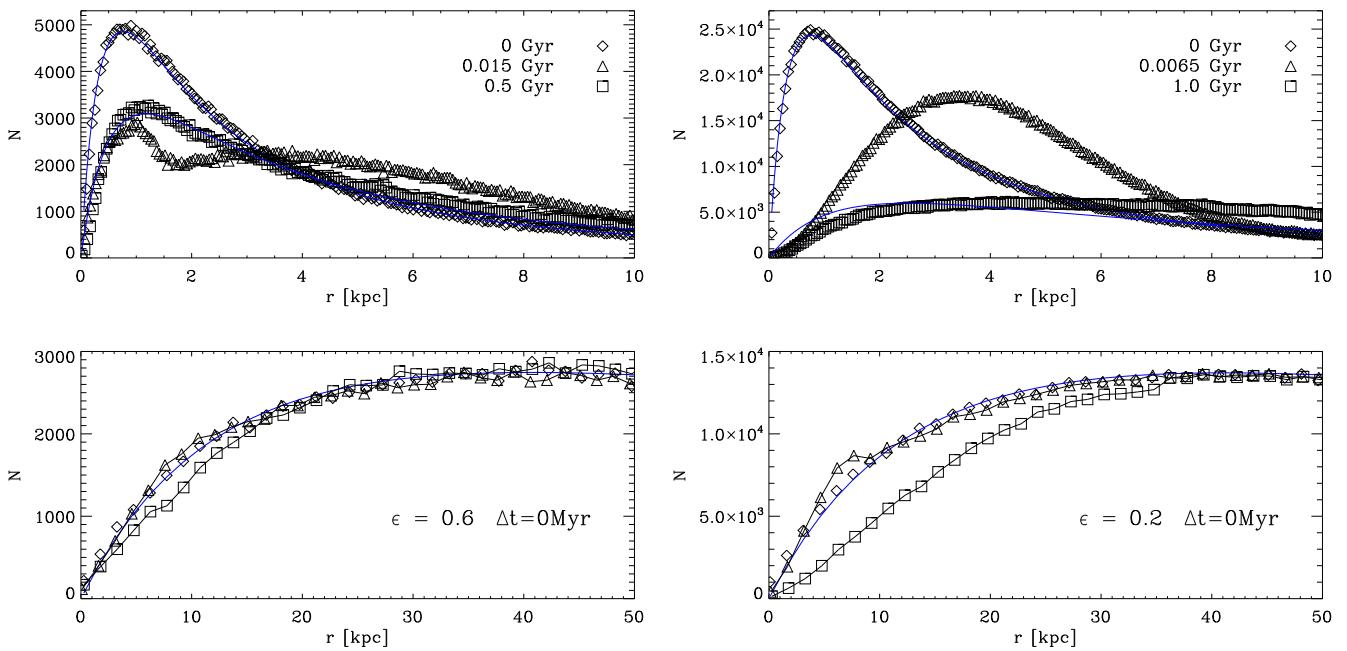


Figure 5. Two examples of the effects of baryon expulsion on the density profiles (shown as radial distribution of particles) of baryons (top panels) and DM (bottom panels, showing only the inner region). The left column refers to $\epsilon = 0.6$ and $\Delta t = 0$, while the right one is for $\epsilon = 0.2$ and $\Delta t = 0$. We plot three snapshots, i.e. the initial one, one wherein the baryons are far from equilibrium, and the final one (times indicated in the bottom panels). The blue solid lines are χ^2 fits to the distributions with Hernquist and NFW profiles respectively, which we show in the former case only for the initial and final states, and in the latter only for the initial one.

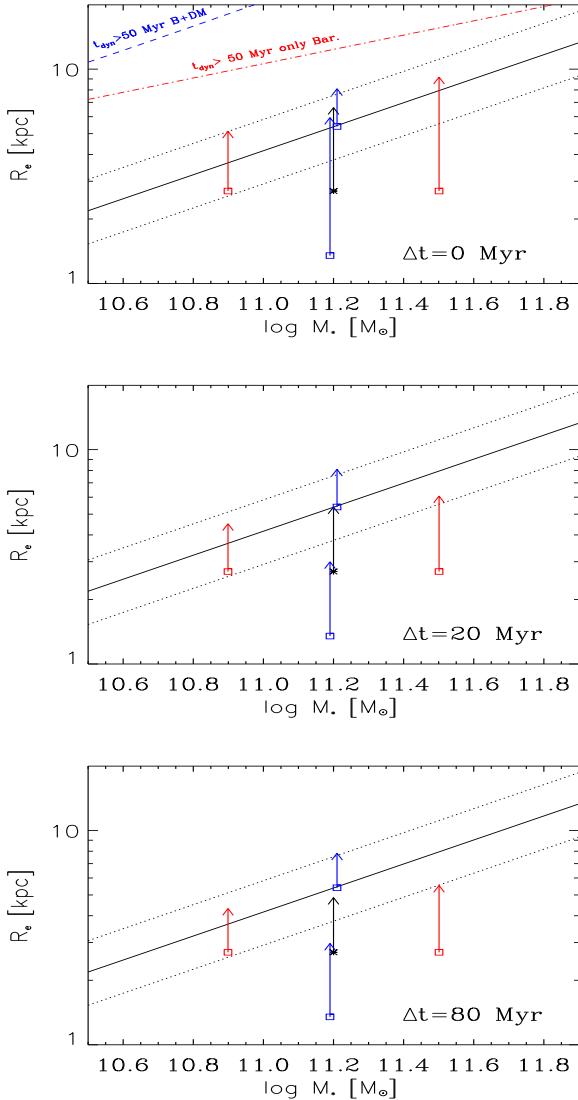


Figure 6. Initial position (points) of our runs in the stellar mass-size plane, and its evolution (arrows) due to gas ejection amounting to 60% of the initial baryonic mass (i.e. for $\epsilon \equiv M_{B,fin}/M_{B,ini} = 0.4$). The various panels refer to different expulsion times Δt , as indicated. The starred point with black arrow represents the reference model, while the other four points-arrows show the behaviour of systems having an initial baryonic mass or radius twice smaller or greater (while the DM halo remains identical). For ease of reading, we have artificially displaced slightly in mass the points corresponding to variations in radius. The solid diagonal line is the mass-size relationship for local ellipticals (Shen et al. 2003), with the 1σ dispersion depicted by dotted lines. The upper panel shows the lines above which the initial dynamical time is $\gtrsim 50$ Myr, without DM (dot-dashed, Eq. 10) or including it (dashed, Eq. 9) (see Section 5).

than a few dynamical times, i.e. less than $\sim 20 - 30$ Myr for the adopted initial configuration. This is at least a factor 20 less than the estimated ages of stellar populations in high- z compact galaxies ($\gtrsim 0.5 - 1$ Gyr; e.g. Longhetti et al 2007; Damjanov et al. 2009). Even taking into account generous uncertainties of these estimated ages, it seems clear

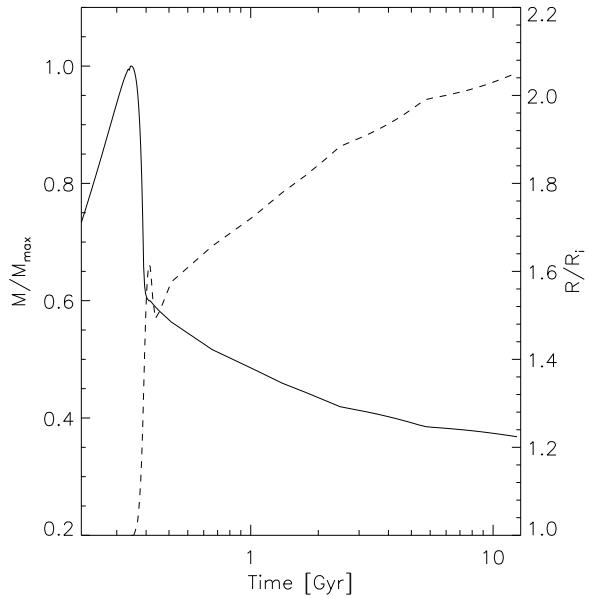


Figure 7. Example of evolution of the total baryonic mass (star forming gas+stars) in the G04 model for co-evolution of SMBH and spheroids (solid line, left axis), and the increase in size (dashed line, right axis) according to our corresponding simulation. The mass is measured in units of M_{max} , which is the maximum value of the total baryonic mass (stars+cold gas) attained during its formation. This is reached just before the galactic winds eject the cold gas and stop further star formation. The abrupt decrease of the mass after ~ 0.3 Gyr marks the ejection of the cold gas, not yet converted into stars, by the AGN-driven wind, while the subsequent slow decrease is due to stellar mass returned to the ISM, under the assumption that the galaxy potential cannot retain it. See text for more details.

that a substantial contribution of galactic winds to the size evolution observed so far can be safely ruled out. Nevertheless, this process should have had a role in deciding the size of ETGs, if (QSO-driven) galactic winds caused their sudden death, but its signature should be searched for in much younger systems. This poses huge observational challenges with present facilities.

Since the expansion timescale is proportional to the dynamical time $t_{dyn} \propto M^{-0.5} R^{1.5}$, it could be suspected that the problem originates from our choice of initial conditions, such as an excessive initial baryonic mass or an insufficient initial radius. However to get a factor $\gtrsim 10$ increase (a minimal requirement) of the dynamical time, the initial size should be increased at least by a factor $\gtrsim 5$, or the mass decreased by a factor $\gtrsim 100$. Actually, even these large changes of the baryonic distribution would not suffice, since in both cases the fixed DM component would become important to set the dynamical time in the galactic region (Eq. 9). Anyway, in both cases the initial state of the system would already lie well above the observed *local* size-mass relationship. This is illustrated by lines in the top panel of Fig. 6, delimitating the region of the plane $R_e - M_*$ where $t_{dyn} \gtrsim 50$ Myr. As can be appreciated there, the inclusion

of a DM contribution to estimate t_{dyn} makes the argument even stronger. Moreover, our standard initial conditions put the system about a factor 2.5 below the $z=0$ size-mass relationship, if about half of the baryons are in stars (in other word if $\epsilon \sim 0.5$). A non negligible fraction of compact high- z ETGs are found up to a factor $\sim 3 - 5$ below this relationship (e.g. Zirm et al. 2007, Toft et al. 2007, Van Dokkum et al. 2008, Cimatti et al. 2008, McGrath et al. 2008, Cassata et al. 2010). For these, the initial dynamical time is even shorter, exacerbating the problem, as we anticipated in Section 3. On the other hand, given the anti-correlation between initial size and expansion R_f/R_i achieved after mass loss, discussed at the end of Section 4 and shown in Fig. 6, also for these extremely compact objects it is conceivable to get final sizes close to the locally observed ones.

We have also verified, with a few sample simulations, that this general conclusion on the shortness of the expansion timescale is not significantly affected by assumptions such as that the gas and stars share the same profile before ejection of the former, or that this ejection occurs homogeneously in the system. The same holds true for different choices of the density profile of the DM and baryonic components (Eq. 3 and Eq. 7), provided they describe in a reasonable manner the density distributions of the respective mass distribution.

Even in the case of expansion driven by stellar mass loss the problem of the excessive shortness of the expansion timescale is likely important, though less clear cut. Indeed, Damjanov et al. 2009 pointed out it, basing their reasoning on the star cluster approximation reviewed in Section 2, and in the performing simplified estimates of mass loss due to stellar evolution. They found that the fraction of mass lost during the passive evolution of stellar populations can be as large as 30-50%, depending on the IMF, but the majority of this loss occurs in less than 0.5 Gyr (see their figure 7). This timescale is still younger than the typical estimated ages of high redshift compact ETGs. However, it should be pointed out that the details of this result depend also on the adopted recipes for stellar lifetimes and yields. These ingredients have some uncertainty (e.g. Romano et al. 2005). As a result, it cannot be totally excluded that passively evolving ETGs lost 20-30% of the residual baryonic mass even ~ 0.5 Gyr after the end of their main star forming phase. This would produce a small (due also to the relatively inefficient size increasing effect of slow mass loss, Figs. 1 and 2), but not negligible, contribution to the claimed size evolution. Moreover, in this case the uncertainty on the relatively difficult estimation of ages could have some importance, at least for the youngest observed high- z compact ETGs.

To better illustrate the above points, we show in Fig. 7 the result of a sample simulation, applied to a specific semi-analytic galaxy formation model including both processes, namely QSO driven galactic wind and mass loss from stars due to stellar evolution. The figure displays the time evolution of baryonic mass as predicted by the G04 spheroid-SMBH co-evolution model (with the parameters as in Lapi et al. 2006), in a $10^{13} M_\odot$ DM halo that virializes at $z = 4$, together with the corresponding increase in size, computed with the procedure described in the present paper. The abrupt decrease of the mass after ~ 0.3 Gyr marks the ejection of gas by the AGN-driven wind. Note that, though this is a relatively fast process, it still does occur, according

to the adopted recipes, on a timescales of a few t_{dyn} . This holds true over a wide range of model parameters. As a consequence, the corresponding puffing-up is milder (a factor ~ 1.5) than the maximal one (for a given ϵ), achieved when $\Delta t = 0$. The subsequent slow decrease of mass and moderate increase in size (a further factor ~ 1.35 , for a total expansion of ~ 2), is due to stellar mass returned to the ISM, under the assumption that the galaxy potential cannot retain it. The size expansion achieved after the epoch in which stellar populations are older than $\sim 0.5 - 1$ Gyr is 25% - 20%.

In conclusion, the putative puffing up related to large scale galactic winds, quickly ejecting a substantial fraction of baryonic mass, can be an important phenomenon, but is still not observed. In particular, it cannot be invoked to explain the size evolution of ETG from $z \simeq 2.5$ to $z = 0$ observed in the presently available data. By converse, the secular adiabatic expansion, related to the mass returned to the ISM by stars during the final stages of their evolution, could contribute, but not dominate, the observed size evolution of ETGs. Nevertheless, it is relevant to further investigate also this contribution, since it seems that none of the processes or biases considered so far can explain alone this evolution (e.g. Hopkins et al. 2010).

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